Lattice Confinement Fusion

Cryobot Workshop
JPL
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NIAC 23 Project:
Accessing Icy Worlds using Lattice Confinement Fusion (LCF) Fast Fission

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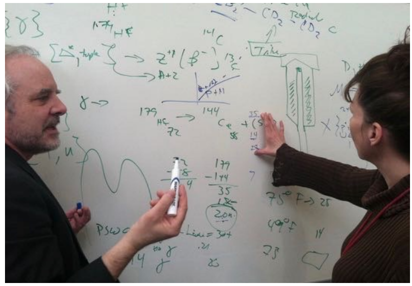


Overview

- Introduction
- Mission Context
- Robotic Probe Specifications/Options
- Innovation
  - How Lattice Confinement Fusion (LCF) Works
  - Hybrid Fusion Fast Fission
- Potential Impact
- Takeaways

Introduction

- Ocean Worlds Exploration Program
  - Search for Extraterrestrial Life
  - Ceres, Europa, Enceladus, Pluto
  - Challenges:
    - Extreme operating environmental conditions
    - Break through up to 40 km thick ice

- Robotic Probe
  - Small, robust, long-lived electrical energy and heat source
  - Traditional nuclear power systems require significant radioactive shielding
  - Enriched actinide-based systems: significant fabrication, safety, launch costs

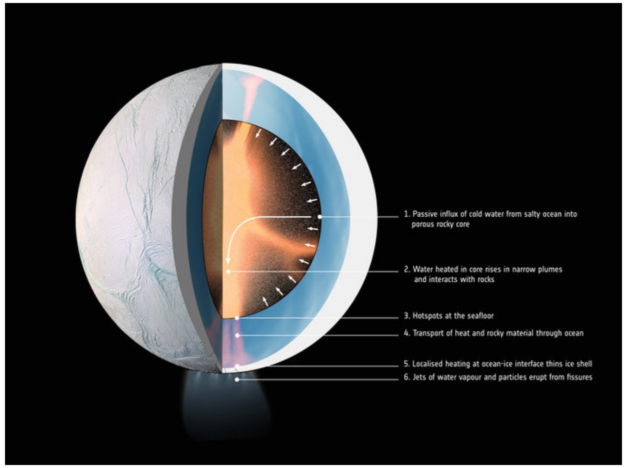
- Cryobot reference[1]
  - Power Density > 1 W/cc
  - Total (thermal) power: 8 – 12 kW
  - Lifetime: 2-6 years, operating at full power
  - Maturity: TRL 6, flight ready in ~10 years

[1] B. Hockman, et al., “PRIME: “Probe using Radioisotopes for Icy Moons Exploration” A Comprehensive Cryobot Architecture for Accessing Europa's Ocean” Paper_1028536_extended_abstract_90601_0

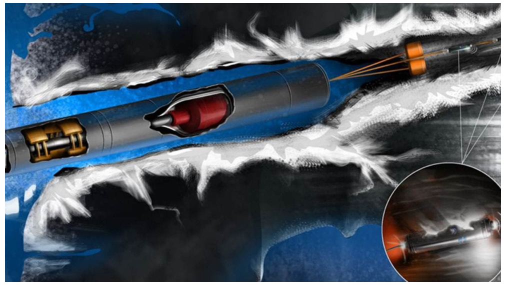
Mission Context

- Icy World Exploration
  - Proposed probe capable of powering the probe and a drilling mechanism with enough Watt-electric and Watt-thermal to accomplish its mission
  - Heated and/or (ultra) sonic drilling mechanism will enable the probe to travel through icy crusts
  - LCF-driven Fast Fission can provide Nuclear Electric Propulsion for shorter journey
  - Ceres, Europa, Enceladus and Pluto are icy world candidates

Europa Cutaway



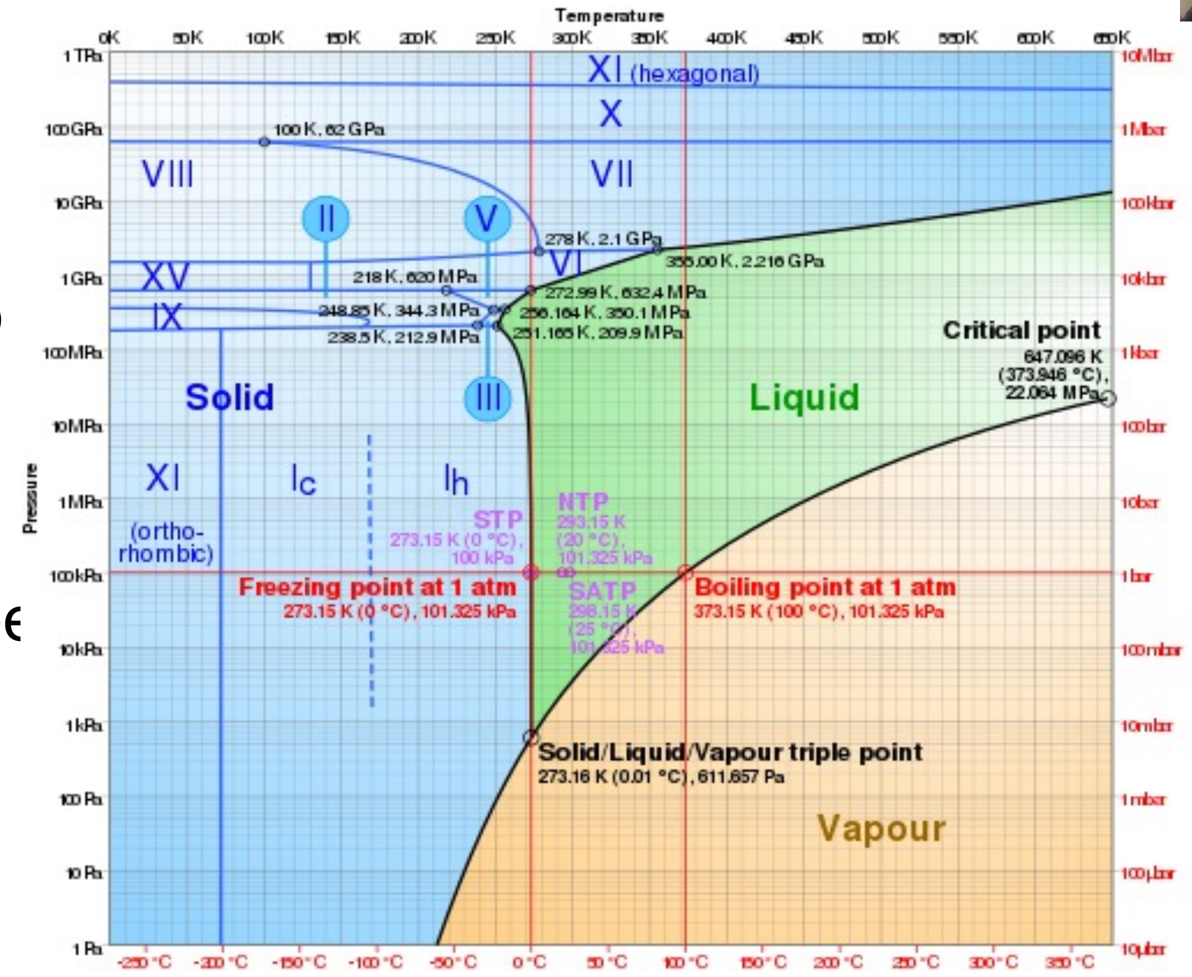
Enceladus Cutaway



GRC Tunnelbot

Lattice Confinement Fusion

- Addressing Icy World Conditions
  - Icy crust likely exist over a pressure range from vacuum to possibly over 10 kbar
  - Temperature range from cryogenic to > 270 ºK
  - Various ice phases impact probe travel rate and pressure[1]
  - Sub-surface lakes likely[2]
  - *With these conditions, variable power output is required*



https://commons.wikimedia.org/wiki/File:Phase_diagram_of_water.svg

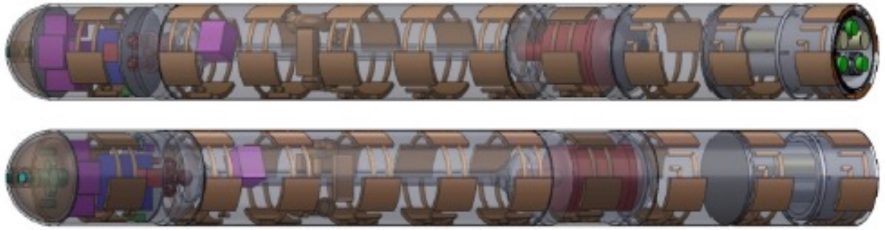
[1] B. Journaus, et al., "On the identification of hyperhydrated sodium chloride hydrates, stable at icy moon conditions", PNAS, (21Feb23)

[2] R. Culbert, *et al*., "Double ridge formation over shallow water sills on Jupiter's moon Europa", *Nature Communications*, **13:**2007 (2022)

Lattice Confinement Fusion

Robotic Probe Specifications/Options

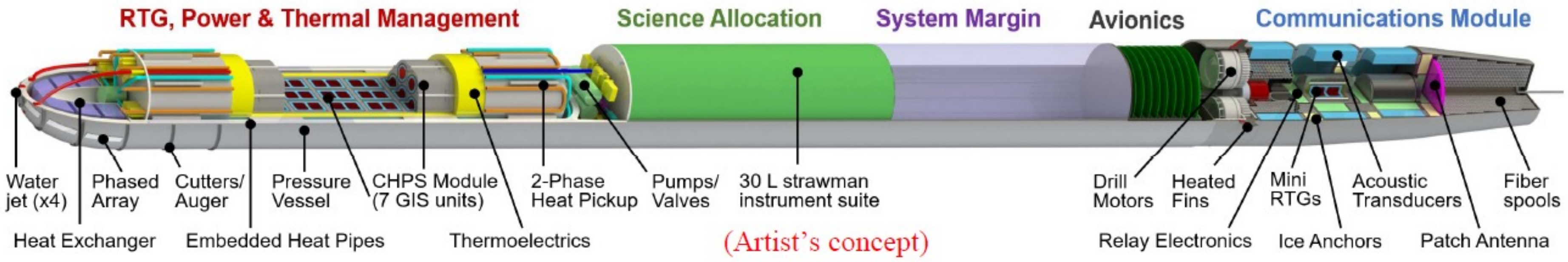
- Europa Tunnelbot[1]



Subsystems:
Science
Thermal
Attitude Determination and Control
Communications
Power
Command and Data Handling
Structures

Figure 16.—Additional transparent views of Europa Tunnelbot reactor case.

- Cryobot[2]



(Margined)

System	
Mass	**350 kg**
Volume	150 L
Length	3.1 m (cylinder) 3.9 m (total)
Diameter	23 cm

Mobility System	
Speed (cold layer)	4.4 km/yr
Speed (warm layer)	17.2 km/yr
Detectable hazard	1 cm (estimated)
Steering radius	10 m (estimated)
Debris Removal	Waterjet / drill

Power/Thermal System	
Total Heat	10.5 kWt
Peak Power	1 kWe
Skin temperature	25 C
WJ flow rate	3 L/min
Survival pressure	53 MPa

Communication System	
Data (primary)	1 kbps
Data (secondary)	100 bps
# Relays	3
Relay power	10 W
Fiber Length	70 km

Figure 1.—Tunnelbot reaching ocean after deploying communication repeaters and anchor (artist impression).

[1] S. Olesobm *et al*, "Compass Final Report: Europa Tunnelbot", NASA/TP-2019-220054.
[2] B. Hockman, *et al*., "PRIME: "Probe using Radioisotopes for Icy Moons Exploration" A Comprehensive Cryobot Architecture for Accessing Europa's Ocean" Paper_1028536_extended_abstract_90601_0

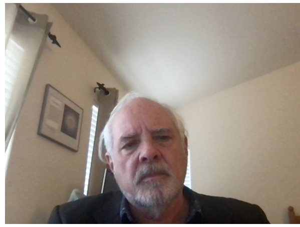
Innovation

- Lattice Confinement Fusion (LCF) Technology
    - Develop a non-fissile, compact, scalable nuclear energy source sufficient to power and provide heat for melting and boring through icy shelves with untethered, autonomous probes.
    - Possible high I_{sp} (specific impulse) Nuclear Electric Propulsion (NEP)
    - Future development could go beyond the icy-moon mission to a lightweight power source for human & robotic missions.

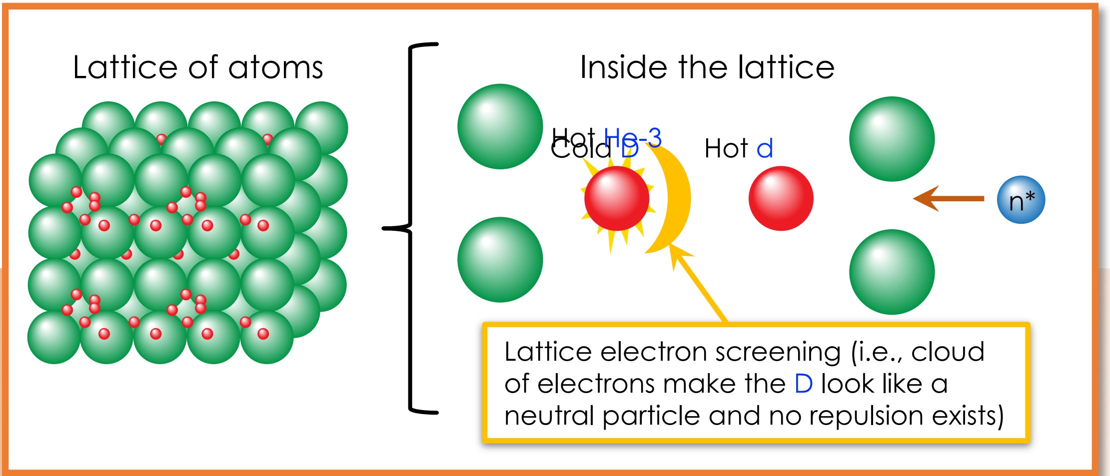
Depiction of the ocean underneath Europa's icy layer

Lattice Confinement Fusion

How LCF Works



- Traditional fusion: Heats plasma 10x hotter than center of sun – *hard to control*
- LCF addresses the pressure, temperature, and containment challenges with fusion
    - Heats **very few** atoms at a time
    - Approaches solar fuel density
    - Lattice provides containment

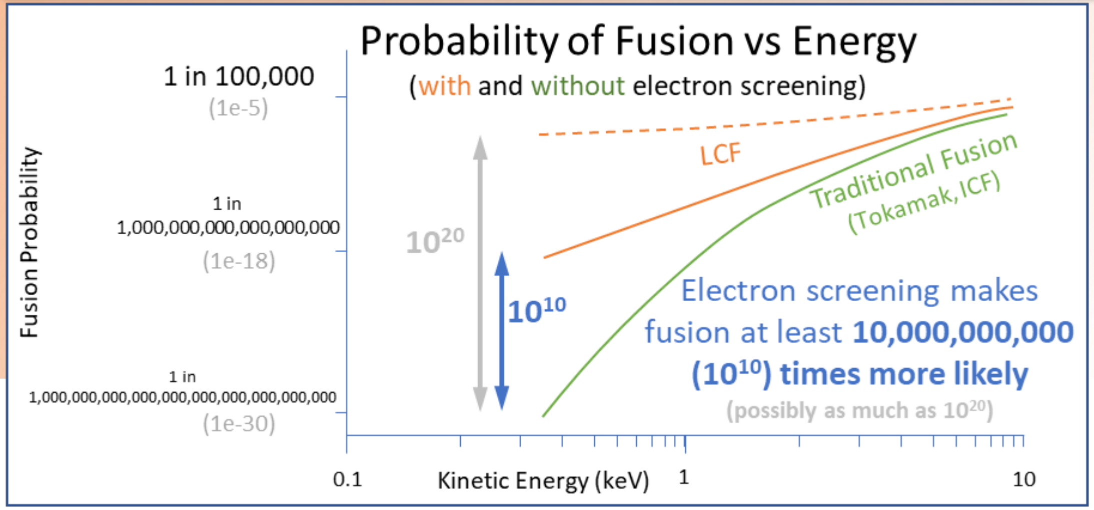


Technical Details Simplified

Part A: **Electron Screening**
(increases fusion probability)

Part B: **High Fuel Density**
(billion times more dense than traditional fusion)

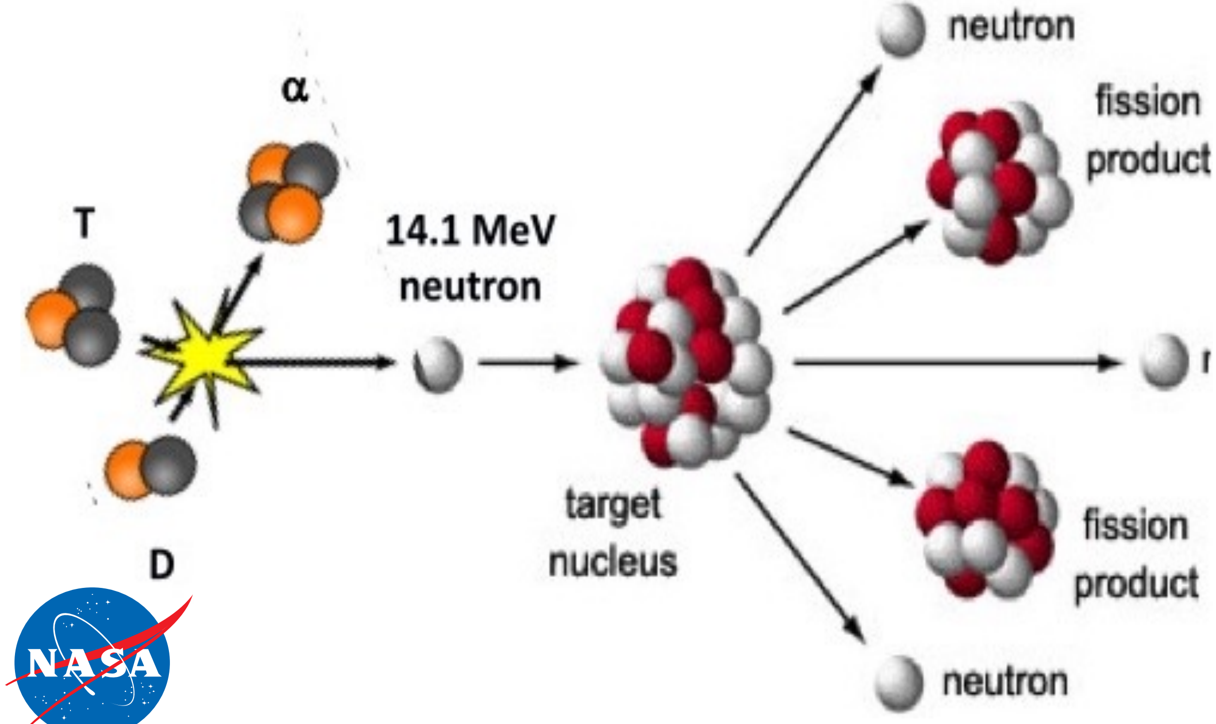
A + B + Trigger = Viable Fusion



https://www1.grc.nasa.gov/space/science/lattice-confinement-fusion/

Hybrid Fusion-Fast Fission

- Takes advantage of both processes
  - Fusion reactions provide the neutrons to fission non-fissile material
  - Require ~2MeV neutrons to fission Th and natural U
  - Fusion reactions can provide up to 14.1 MeV neutrons



Fusion Reaction	MeV	Occurrence	Useful particle energy (MeV)
$D(d,n)^3He$	4.00	primary ≈ 50%	n=2.45
$D(d,p)T$	3.25	primary ≈ 50%	p=3.00
$D(^3He,p)\alpha$	18.30	secondary	p=15.00
$D(t,n)\alpha$	17.60	secondary	n=14.10
$T(t,\alpha)2n$	11.30	low probability	n=1 to 9
$^3He(^3He,\alpha)2p$	12.86	low probability	p=1 to 10
Fission Reaction	**MeV**	**Occurrence**	**Useful particle energy (MeV)**
$^{232}Th(n,\gamma)f$	200	high probability	n=1 to 9
$^{232}Th(p,\gamma)f$	200	some probability	p=1 to 10
$^{238}U(n,\gamma)f$	200	high probability	n=1 to 9
$^{238}U(p,\gamma)f$	200	some probability	p=1 to 10

Potential Impact

- Probes for icy moons require unacceptable amounts of ^{238}Pu isotope.
- A small, low-mass, variable power source is needed.
- New hybrid approach yields a variable output power source smaller than existing fissile reactors.
- Non-fissile alternative to high-enriched uranium (HEU) or high-assay, low-enriched uranium (HALEU) core saves uranium enrichment, security and launch safety costs.
- Efficient operation with reactor thermal waste heat allows probe to melt and/or vibrate through ice shelf.

Takeaways

- Hybrid Fusion-Fast Fission Power system
  - *No HEU or HALEU necessary*
  - *Built on NASA GRC[1] and US Navy research[2] published in Phys Rev C and elsewhere*
  - *With scaling, suitable for ice crust penetration and power*
  - *Variable output power possible so probe is throttleable*
  - *Compact system supports small size of the probe*
- Recognition of Icy World ice-phase temperature and pressure changes
  - *Requires power/penetration flexibility*
  - *Possible near-surface ice pools[3]*
- Combined ice melting/ultrasonic penetration
  - *Takes advantage of skin layer adjacent to probe*

1. Pines, *et. al*., "Nuclear Fusion Reactions in Deuterated Metals", *Phys Rev C*., **101**, 044609 (2020)
2. Mosier-Boss, *et al*., "Investigation of Nano-Nuclear Reactions in Condensed Matter", *Defense Threat Reduction Agency*,(2016).
3. R. Culbert, *et al.,* "Double ridge formation over shallow water sills on Jupiter's moon Europa", *Nature Communications*, **13**:2007 (2022)

Acknowledgments

- Thanks to the Cryobot Workshop Organizers for inviting us!
- We’re looking forward to learning more from you as to the changing requirements
- While looking forward to increasing the TRL of LCF Fast-Fission

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